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NBS TECHNICAL NOTE 538

Automated Fingerprint Identification

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Automated Fingerprint Identification

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Contents

Automated Fingerprint Identification

by J.H. Wegstein

A procedure is described for determining whether two fingerprint impressions were made by the same finger. The procedure uses the x and y coordinates and the individual directions of the minutiae (ridge endings and bifurcations). The identity of two impressions is established by computing the density of clusters of points in Δx - Δy space where Δx and Δy are the differences in coordinates that are found in going from one of the fingerprint impression to the other. Experimental results using machine-read minutiae data are given along with results from a previously reported procedure that utilized constellations of minutiae in its matching process.

Key words: Computerized-fingerprint-identification, fingerprint, pattern recognition.

1. Introduction

This paper follows a previous paper [1.] that describes a procedure for matching fingerprint impressions by computer using two types of minutiae: ridge endings and bifurcations. With a fingerprint impression in the first quadrant, data is obtained by reading the X coordinate, Y coordinate, and the angle θ which the minutia direction makes with the X axis for each minutia in the print. When the data is taken manually, θ is measured in degrees and X and Y are measured in <u>units</u> of one tenth millimeter on an actual fingerprint or a millimeter on a ten-fold enlargement of the print. There are about 80 minutiae in an average rolled fingerprint.

To test the performance of a matching procedure, the minutiae data for a set of fingerprints is entered into a computer file. Next, working with minutiae data for a second set of prints (the search prints), the computer compares each of the search prints with each of the prints in the file. Thus, if there are N prints in the file and n search prints, the computer will make n x N comparisons in a given matching run. Each comparison yields a score and the higher the score the more likely it is that both of the prints being compared came from the same finger. In the course of adjusting parameters and improving matching procedures many thousands of pairs of prints have been compared. These experiments have used data that was read manually at the National Bureau of Standards as well as data that was read by machine at the Autonetics Division of North American Rockwell Corporation and Cornell Aeronautical Laboratory, Inc.

2. Tools for Performance Analysis

In the development of pattern recognition techniques it is essential to have ways of measuring performance. New results, after a change in the recognition technique, must be compared with previous results and ultimately it should be possible to compare the achievements of one research effort with the achievements of others in the same field of endeavor.

One tool for displaying the results of fingerprint recognition as well as voice signature recognition is a score matrix. For example if a set of five fingerprints identified as XIII-I, XIII-2,---, XIII-5 is compared with a file of twenty prints identified as XIV-1, XIV-2,---, XIV-20, the results can be displayed as shown in Figure 1. Each of the 100 pairs of prints are compared and the resulting score is entered in the matrix. In Figure 1 prints XIII-n and XIV-n came from the same finger where n=1, 2,----5. Therefore the leftmost diagonal should contain the highest scores in the matrix.

In voiceprint file searches, Tosi [2.] has defined a closed task as a file search in which the search print is known to be in the file. The searcher must simply find the best match. Analogously, if print XIII-2 is known to be in the file, then one need only look for the highest score, 80, in the XIII-2 row. Tosi has defined an open task as a file search in which the searcher does not know if the print being sought is in the file. This is a difficult task because the searcher must judge if the degree of match exceeds some threshold value. By analogy, if a score of 70 is set as a threshold for a match in this fingerprint file search, then XIII-1, XIII-2, and XIII-3 would be correctly identified. However, the search would conclude that XIII-4 and XIII-5 were not in the file. The discrimination matrix can be reduced to a binary matrix by recording only scores that exceed the threshold as X and leaving all other spaces blank.

If a computer is comparing an unknown print with prints in a file as a closed task, the computer will always indicate that some print from the file has the highest matching score and a fingerprint expert must compare the unknown print with the file print to determine if they are from the same finger. In a practical system where some of the unknown prints are not in the file, the expert must still look at some file print for each of the unknown prints. On the other hand, if the computer is operating in the open task mode, it will indicate only those prints from the file that exceed some matching score threshold. The obvious objective in the design of a matching procedure is to achieve such a level of discrimination that only those pairs of prints that came from the same finger will exceed the matching score threshold and require verification by the fingerprint expert.

In order to compare the performance of one matching run with another, one might reduce the data in a discrimination matrix to two numbers: M the percentage of misses, and F the percentage of false

matches. Let

TM = total number of matches that should have occurred

TF = total number of failures to match that should have occurred

MS = number of misses

FM = number of false matches

then $M = \frac{100\ MS}{TM}$

$F = \frac{100\ FM}{TF}$

In Figure 1, TM = 5, TF = 95 and if a threshold score has been set at 50, MS = 1 and FM = 3. Therefore F = 3.2% and M = 20%.

The values of F and M can be plotted against their corresponding threshold scores as shown in Figure 2. As the threshold value decreases, the percentage of misses decreases as is shown by the solid line. Unfortunately, this is accompanied by an increase in the number of false matches. When a large number of prints are compared, the curves appear to be exponential curves as shown in Figure 3. The point P where the curves cross is of considerable interest in perfecting a matching procedure. P should be as low as possible when a very large number of fingerprints are compared.

The F and M scores are actually impractical for tuning and improving matcher performance with the available general purpose computer because more than 26 pairs of prints in a given matching run exceeds the storage capacity of the high speed memory. When a promising level of performance is achieved, there will be a significant portion of the curves where F and M are zero as seen in Figure 4. Accordingly, three other scores are used: OS, CS, and AA. <u>OS</u> is used to measure performance as an <u>open</u> task and is the highest score for a pair of prints that should not match divided by the lowest score for a pair of prints that should match multiplied by 100 (rounded to the nearest integer). Using the data from Figure 1,

$$OS = \frac{55}{37} \times 100 = 149.$$

<u>CS</u> is used to measure performance as a <u>closed</u> task. In Figure 1, the highest off-diagonal score in each row is divided by the diagonal score for that row (where there should be a match) and this is multiplied by 100. Thus, there is a score for each row. The highest (or worst) of these is taken as the score CS. In Figure 1, CS = 124, corresponding to the highest row score, occurring in row 5, where

$$\frac{46}{37} \times 100 = 124.$$

A print is correctly identified if CS < 100, and the objective in this developmental work is to obtain as low a value as possible for CS and OS. One bad print in the set can cause CS and OS to be very high, but the matcher may be doing a relatively good job with the rest of the prints. Accordingly, still another score, <u>AA</u>, is defined as the mean off-diagonal score divided by the mean diagonal score times 100. In Figure 1,

$$AA = \frac{19.95}{76.6} \times 100 = 26$$

It is desirable to have as low a value as possible for AA.

3. Experimental Results with Constellation Matcher

The fingerprint matcher reported in NBS Technical Note 466 [1.] as well as several subsequent variations of this matcher compared two fingerprint impressions by finding several minutiae (a constellation) in one print that approximately coincide with a similar constellation from another print. Relative positions of the minutiae as well as direction angles of the minutiae were utilized in computing whether or not there was a coincidence. To minimize the amount of computer time and data storage required, only a portion of the available minutiae from a fingerprint was used. Only those minutiae in a circle of 6mm radius centered at the core of the print were used, and there was an average of about 24 minutiae in the circle on the prints used. Using minutiae that were carefully read manually, matching twenty pairs of average fingerprint impressions after extensive parameter tuning and matcher modifications led to the results shown in Figure 4. Here, the number of minutiae in the constellation being matched is used as the score and hence as the discrimination factor. The point P has been lowered to zero, but the range in the number of minutiae in the matching constellations is discouraging. The maximum number of nine matching minutiae found here fall short of the 12 or more predicted by Caudra [3.] as necessary to get adequate odds in favor of recognizing two prints from the same finger when working with a large file. If other parameters in the matcher are "loosened up" such as increasing the allowable difference in position of matching minutiae, then the number of false matches invariably rises.

The reason for a false match can be seen by referring to Figure 5. Minutiae tracings from fingerprint impression XIII-11 (enlarged 10 times) are superimposed on tracings from impression XIV-2 which came from a different finger. Minutiae XIII-11-48 is positioned to coincide with minutia XIV-2-13. If the maximum allowed difference in coordinate values for the other minutiae are:

$$\Delta X = 6 \text{ units}$$

$$\Delta Y = 6 \text{ units}$$

$$\Delta\theta = 15 \text{ degrees.}$$

then the two constellations of seven minutiae produce a false match. If parameter ΔX or ΔY is reduced to 5 units then this false match is eliminated.

On the other hand, these same parameters may fail to produce matches of two impressions from the same finger because of ever-present distortions. All rolled fingerprint impressions tend to be stretched or twisted in varying amounts. To illustrate a worse-than usual case, minutiae from impression IIP2 are superimposed on minutiae from impression IIP8 in Figure 6. Both impressions are from the same finger and minutia 79 is positioned to coincide with minutia 79'. While minutiae 79, 33, and others to the left tend to coincide, minutiae to the right move further and further apart. Furthermore, distortions may be strangely localized. In Figure 7 two different impression IIP5 and IIP6 from the same finger are superimposed with minutiae 28 and 28' coinciding. While the degree of coincidence is good in the upper left, lower left, and lower right, there is X-distortion in the upper right portion of the print.

The method of matching pre-defined portions of fingerprints by starting with some minutia as a nucleus and developing a constellation of coinciding minutiae has been unsatisfactory. The main reason for this is that only five minutiae were tried as the nucleus for a constellation. This number was limited to five in order to hold down the amount of computing time needed on a general purpose computer to make extensive matching tests. It may be that trying more minutiae as a nucleus would result in satisfactory matching. To adequately test this method of matching prints, it will either be necessary to use more general-purpose computer time or use a special-purpose device designed for minutiae matching such as that described by Thiebault [4]. which can utilize parallel operations for very fast matching.

4. A Statistical Matching Procedure

In spite of the distortion shown in Figure 7, it is desirable to take advantage of those pairs of minutiae such as 28, 27, 34, 35, 52, 53, 70, 74, and 75 and others not shown that do coincide. To illustrate how this can be done, some minutiae data from four prints will be used. In Figure 8, the print A and B data are from two different prints made by the same finger and the print C and D data are from prints from two different fingers. Minutiae i in print A is the same as minutiae j in print B if i = j. Minutia 6 (labeled B6 in Figure 9) is not found in print A. The minutiae of both prints are plotted in Figure 9. This is typical of the appearance of superimposed minutiae from two prints that have been read by machine. One print is rotated about six degrees and is shifted about 35 units in the x direction with respect to the other print, but, of course, this information is unknown to the computer when it attempts to match these prints. Figure 10 shows the superimposed minutiae from prints C and D.

The M19 Matcher

The simplest version of the statistical matcher, known as M19, begins by computing

$$\Delta x = x_i - x_j$$

$$\Delta y = y_i - y_j$$

$$\Delta\theta = \theta_i - \theta_j$$

for all possible combinations of pairs of minutiae. Only those pairs of minutiae that satisfy the following conditions simultaneously are retained.

$$|\Delta x| \leq LS$$

$$|\Delta y| \leq LS$$

$$|\Delta\theta| \leq L\theta$$

If the matcher parameters have the values

$$LS = 60$$

$$L\theta = 25$$

then the resulting difference table for prints A and B is shown in Figure 11 and the difference table for prints C and D is shown in Figure 12. These points can be plotted in a Δx, Δy coordinate system as shown in Figure 13 for prints A and B and in Figure 14 for prints C and D. If the prints are from the same finger, then many points will tend to be in a cluster as seen in Figure 13. If the prints are from different fingers, then the points tend to be randomly located over the entire area. It will be noted that there is no pronounced clustering in Figure 14.

The task of the matcher is to compute a matching score that increases as the density of the cluster increases. The M19 matcher accomplishes this by starting from each point in the graph and counting the number of steps in the Δx and Δy directions to each of the other points. If this number of steps, TR, is less than a matcher parameter KR, then the quantity KR-TR is added to an accumulating sum R. To see how this works, let KR = 10 and refer to Figure 15 which is an enlargement of the area around the cluster in Figure 13. Point 1,1 in Figure 15 indicates the distance from minutia B1 to A1 in Figure 9. The number of steps from point 1,1 in Figure 15 to any other point exceeds 10 so that nothing is added to R. However, the number of steps from 2,2 to 4,4 is TR=8. Therefore, the score R is increased by KR-TR=10-8=2. Similarly, there are 8 steps between points 2,2 and 5,5 and this increases the value of R to 4. The contributions from all points are shown in

Figure 16 giving a total R=24. The score actually used is RS=R/S where S is the total number of points found in Figure 13. Therefore in this example S=7 and comparing print A with print B yields a score

$$RS = \frac{24}{7} = 3.42$$

The comparison of print C with print D yields a score

$$RS = \frac{14}{7} = 2.00$$

In actual practice, prints that match tend to produce very dense clusters of points in their difference graphs with correspondingly high RS scores. The complete details for the M19 matcher are shown in Flow Chart 1.

The M27 Matcher

The M27 matcher is an expansion of the M19 matcher. It can handle data from prints that are not as accurately positioned in the reader as prints whose data is used by the M19 matcher. As in M19, M27 computes different tables for Δx, Δy, and $\Delta\theta$ where

$$|\Delta x| \leq LS1$$

$$|\Delta y| \leq LS1$$

$$|\Delta\theta| \leq L\theta 1$$

The distribution of the values of Δx is then determined among eleven equal intervals between -LS1 and +LS1. A similar computation is performed for Δy and $\Delta\theta$ except with $\Delta\theta$ the range is from $-L\theta 1$ to $L\theta 1$. The parameter values

$$LS1 = 60$$

$$L\theta 1 = 25$$

used in matching print A with print B produce the same difference table shown in Figure 11. The distributions of these values of Δx and Δy are shown in Figure 17. Prints from the same finger produce peaks in the distribution table, but prints from different fingers produce random distributions. The M27 matcher computes the matching score as did M19 except that it uses only those points in an area 2 x LS2 by 2 x LS2 centered at the peak of the Δx distribution, -36, and the peak of the Δy distribution, 12. These points must simultaneously satisfy the condition that $\Delta\theta$ lies within the range of $\pm L\theta 2$ from the peak of the $\Delta\theta$ distribution which is 0 in this example.

The parameters

$$LS2 = 10$$

$$L\theta 2 = 20$$

$$KR = 10$$

cause M27 to compute a matching score using only the points found in the area enclosed by the broken line in Figure 15. As before, R = 24 but there are only S = 5 points to consider. Therefore, in comparing print A with print B, the M27 matcher produces a score

$$RS = \frac{R}{S} = \frac{24}{5} = 4.80$$

The comparison of print C with print D yields a score of RS = 0. Here there are two peaks in the Δx distribution and in choosing the first or leftmost, the matcher locates the reduced scoring area in a place where no points are close enough together to score. The complete procedure for the M27 matcher is given in Flow Chart 2.

The M32 Matcher

When a fingerprint impression is placed in a reader, whatever may be defined as the center of the print may be displaced from the center of the reader window. The M27 matcher can cope with this situation. However, the direction line of the finger may also be rotated with respect to the y-axis of the reader, and the M27 matcher may then fail to make a correct match. The M32 matcher is designed to overcome this difficulty. It begins by performing the same comparison procedure as the M27 matcher. The computer then re-computes the data for one of the prints being compared to represent the rotation of this print through V degrees from its original position, and another M27 comparison is made. Altogether, the M32 matcher compares the pair of prints seven times with one print being set at each of the following angles with respect to its original position.

$$V = -15°, -10°, -5°, 0°, 5°, 10°, 15°$$

When prints from the same finger are compared, there is always a sharp peak in the graph of RS vs V and the highest of the seven RS scores is taken as the M32 matching score. A typical graph is shown in Figure 18.

5. Experimental Results with Statistical Matchers

Numerous matching runs have been made with these statistical matchers using the NBS UNIVAC 1108 computer. Each run is identified by number and the RS scores from each run are entered in a score matrix as described earlier. Each fingerprint is identified by an Arabic number. The set of search prints is identified by a Roman number and the set of file prints is identified by the next larger Roman number. Each pair of sets is identified by a capital letter.

The score matrix resulting from computer run number 280 is shown in Figure 19. Set XXVI consisting of 14 search prints was compared with set XXVII consisting of 14 file prints. The prints are always ordered such that the scores for prints that should match occur on the diagonal. For example, print 272 and print 1122 are two different impressions from the same finger but print 272 and print 1132 are from different fingers. For this particular run, the minutiae data was read by machine from standard fingerprint cards. The prints were selected as "good looking" rolled prints. Each print was manually positioned in the reader so that the estimated center of the inked impression was at the center of the reader window and the estimated direction of the finger was parallel to the y-axis of the reader. The open task score OS = 60 is found by dividing the highest off-diagonal score, 45 (times 100), by the lowest diagonal score, 75. The closed task score CS = 51 is caused by the second row where 40 is divided by 78. Since both OS and CS are less than 100, the search was a success either as an open or closed search. The score AA = 15 is found by dividing the mean off-diagonal score by the mean diagonal score. It may be feasible to use the score AA from matching runs on small samples of fingerprints to predict the performance in searching large files.

The results of all of the computer runs that have been made using the statistical matchers are summarized in Figure 20. The previous example may be found by referring to computer run number 280 in Figure 20 Part 2. The 28 prints used in this and 7 other runs are identified as Pair F. The smallest number of minutiae read from any of the prints in set XXVI was 81 and the largest number of minutiae was 238. Since the average number of minutiae on a rolled print is about 80, the reader obviously produced many false minutiae, but these false minutiae did not prevent successful identifications in all of the tests with this pair of sets of data.

The same 28 prints were also read by a different reader and the data is identified as pair E consisting of sets XXX and XXXI. See Figure 20 Part 1. Here the prints were not positioned in the reader but instead, the finger-boxes on the fingerprint card were positioned manually in the reader. In some cases the fingerprint was at an angle with the y-axis of the finger-box or the print was not centered in the box. The OS and CS scores in runs 282 and 283 are accordingly high.

Runs 286, 287, 289, 290, and 291 were made to determine the best possible scores attainable with this data. To do this, the minutiae of all 28 prints were plotted using the machine-read data. The plots for each pair of prints from sets XXX and XXXI that should match were manually superimposed and positioned by eye to give the best looking match. The amounts by which each print from set XXX needed to be shifted in the x and y directions and also rotated were measured. These data xx, yy, and v were supplied to the computer and at match time it computed new data representing the corrected position for each print from set XXX prior to computing the match score. The resulting scores show a considerable improvement. The AA scores for runs 289-291 may identify

the lower limit for what can be achieved in practical matching runs. All other matching runs that were made with this type of pre-positioning are identified by the words "See text" in the Notes Column of Figure 20.

6. Discussion of Results

The amount of time required for the computer to compare a pair of prints varys considerably depending on the parameters used and the number of minutiae in each print. Run 282 using the M27 matcher took an average time of 0.1667 seconds to compare a pair of prints. Run 286 using the M19 matcher on the same data took an average time of 0.0845 seconds to compare a pair of prints. This is obviously too slow for the practical search of a large file but it is hoped that these matching techniques can be utilized in a specially built device that can compare a pair of prints in a few microseconds.

Aside from the problems with the matcher itself, the sources of difficulty with minutiae matching can be broken into the following categories, and a discussion of each one follows.

1. Poor quality prints.
2. Only a partial print available.
3. A stretched or twisted print.
4. Print displaced in reader in x and y directions.
5. Print rotated in reader.
6. Reader falsely reports minutiae.
7. Reader misses minutiae.

1. Prints accepted for classification in the Henry system need to be only clear enough so that a fingerprint expert can identify the pattern type and count the ridges between core and delta. Light inking, heavy inking, smudges, and missing portions of the print can often be tolerated in the Henry system. The pairs of prints sets A, B, C, and D were randomly selected from such system files. Set pair C was further limited to those prints where the reader produced more than 50 minutiae per print. The matching runs made with set pairs C and D, using machine-read minutiae from these prints, gave unsatisfactory scores. The runs 199, 218, and 306 with set pairs A and B where the minutiae data was read manually gave better results. Runs 236 and 237 were made on the same minutiae data that produced the results with the constellation matcher reported in Figure 4. Future improvements in minutiae readers may produce some improvement in matching scores. However, it will probably be more effective to change the rules and require higher quality prints for an automated identification system than are required for the Henry system.

The determination of the quality of fingerprints is a very subjective procedure. In the future it may be feasible for the minutiae reader itself to determine the acceptability of fingerprints based on the character and number of minutiae read. The prints for set pairs E, F, and H were selected prior to machine reading on the basis that they looked as though they would read well. The resulting matching scores are very encouraging and produce an optimistic outlook for automating fingerprint identification.

2. Minutiae data from partial prints and particularly latent fingerprints have not been tested with the statistical matchers. However, the outlook is optimistic. The advantage of manually read minutiae data as indicated by the low AA scores with set-pairs A and B may also apply to latent prints where the minutiae data must also be read manually.

3. The low scores with set-pairs E and F suggest that the problem due to flexing and twisting in rolled prints has been solved. Since plain prints tend to be devoid of the flexing and twisting that plagues rolled prints, the nearly equivalent scores with set-pairs F (rolled) and set-pairs H (plain) supports this suggestion.

4. The problem that results from x-y displacement of the print in the reader can be handled by the matchers with suitable parameter adjustments. In particular, the parameter LS in M19 and LS1 in M27 must be set large enough to accomodate any displacement that can occur. Unfortunately, increases in these parameters are accompanied by increase in both computer time and memory capacity requirements.

5. As was seen in Figure 18, the RS scores are very sensitive to the angular orientation of the print in the reader. The print must be oriented within plus or minus 5 degrees for best results. Further experiments should demonstrate that the M32 matcher can handle this problem if the print is not carefully positioned in the reader. However, this too requires additional computer time and would require many more circuit elements in some future specially-built device. Accordingly, it may be more economical to handle both the x-y positioning and angular orientation problem at the reader. The low scores with set-pairs E, F, and H indicate that manual positioning is satisfactory and it may be feasible for this to be accomplished automatically by the reader.

6,7. The number of minutiae missed as well as the number of false minutiae reported by an automatic reader tend to increase as the quality of prints goes down. Accordingly, the remarks under 1 above also apply here. The degree to which these phenomena degrade matcher performance is under study and future improvements in minutiae readers are expected to decrease the number of missed and falsely read minutiae.

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		XIV																			
		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
XIII	1	128	46	8	11	23	8	32	30	13	18	22	42	22	6	53	54	22	19	32	12
	2	55	80	8	12	11	12	28	29	6	12	17	25	18	27	40	34	10	8	8	10
	3	9	11	75	35	16	20	19	9	19	30	23	9	14	13	16	18	36	25	14	17
	4	6	1	19	63	14	16	2	4	11	21	22	23	15	13	17	7	22	18	9	26
	5	11	13	13	27	37	28	14	22	20	40	25	13	16	14	24	20	46	36	29	22

Figure 1. Score Matrix

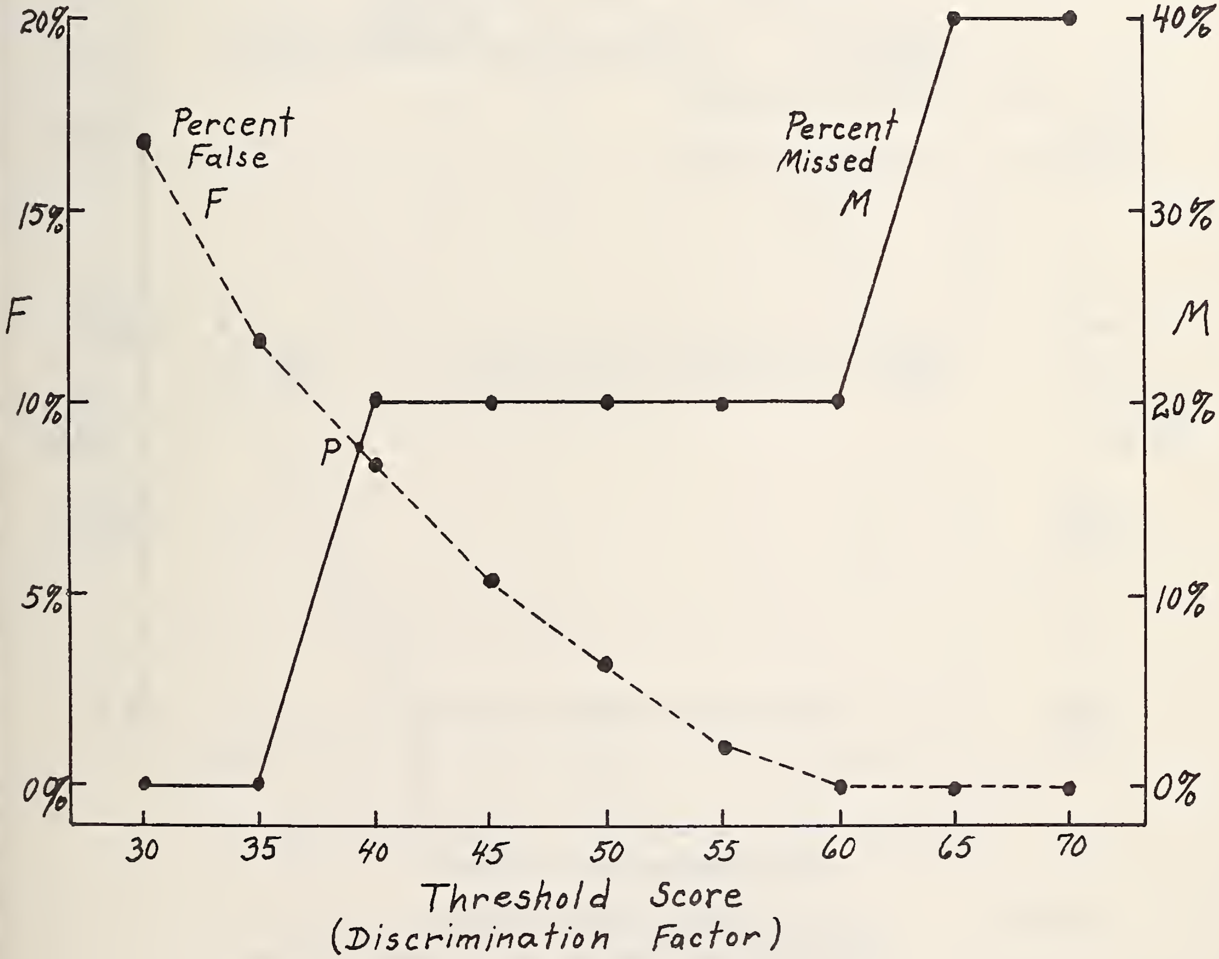


Figure 2. Discrimination Graph Corresponding to Figure 1.

Figure 3. Idealized Discrimination Graph

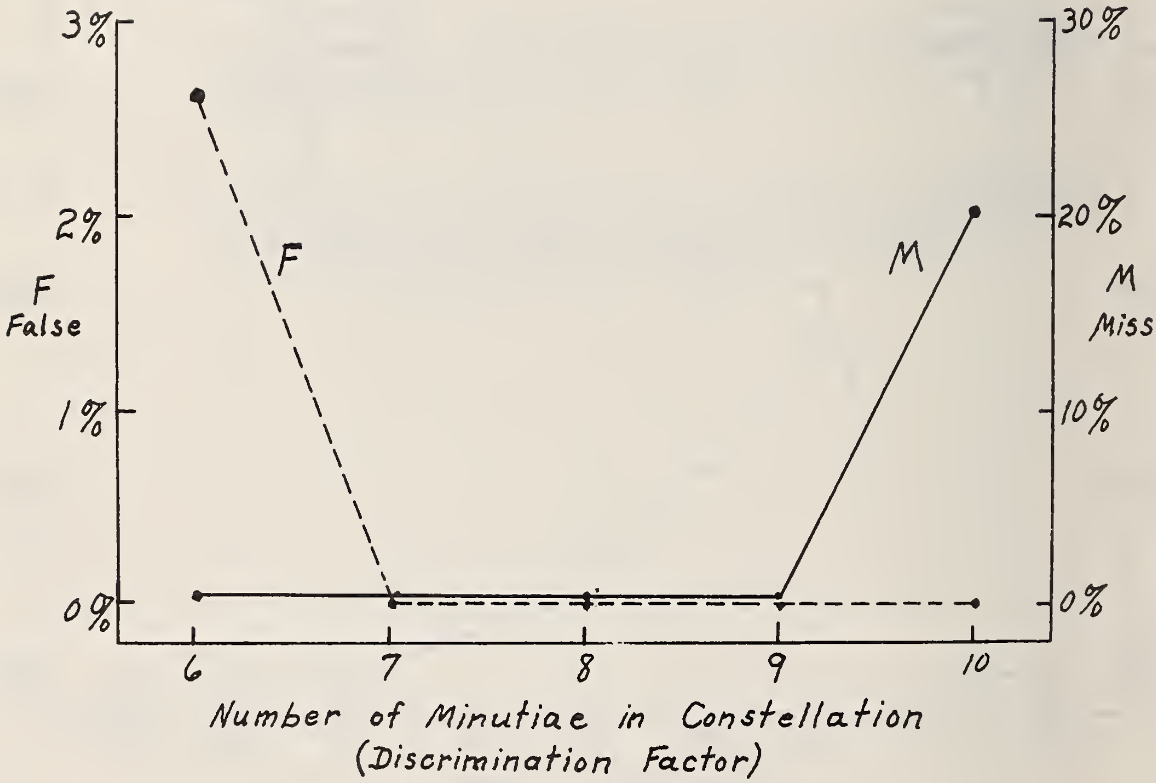


Figure 4. Discrimination Graph Showing Experimental Results with Constellation Matching.
Set XIII vs Set XIV Using Minutiae from 6 mm Radius Circle at Center of Print.

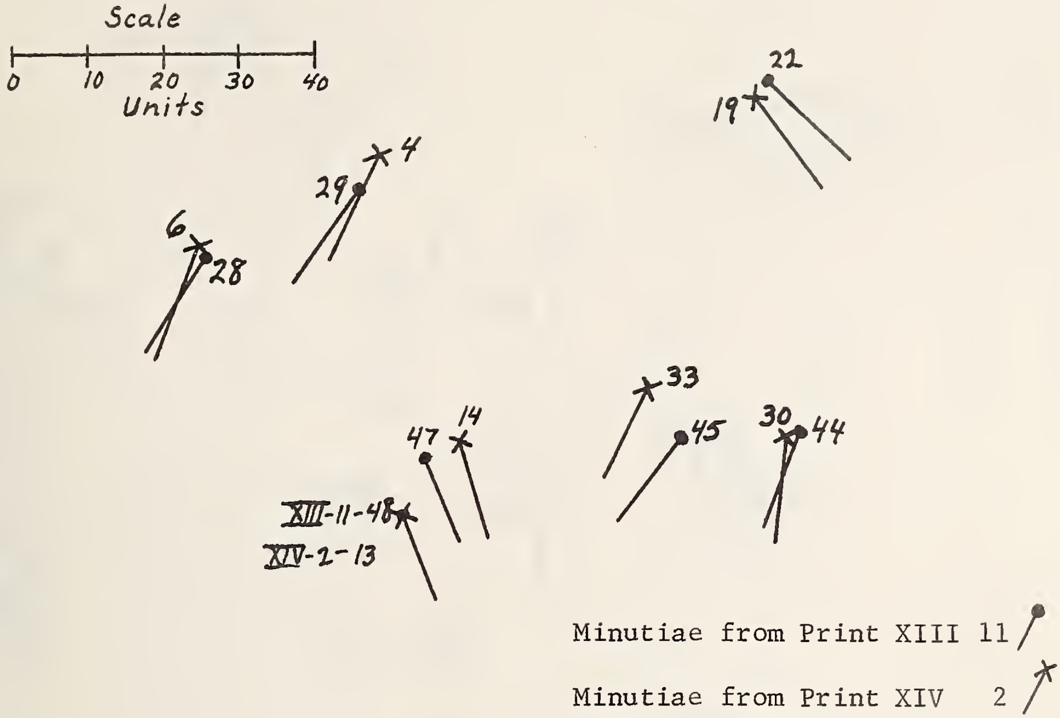


Figure 5. Superimposed Minutiae Tracings from Prints of Different Fingers

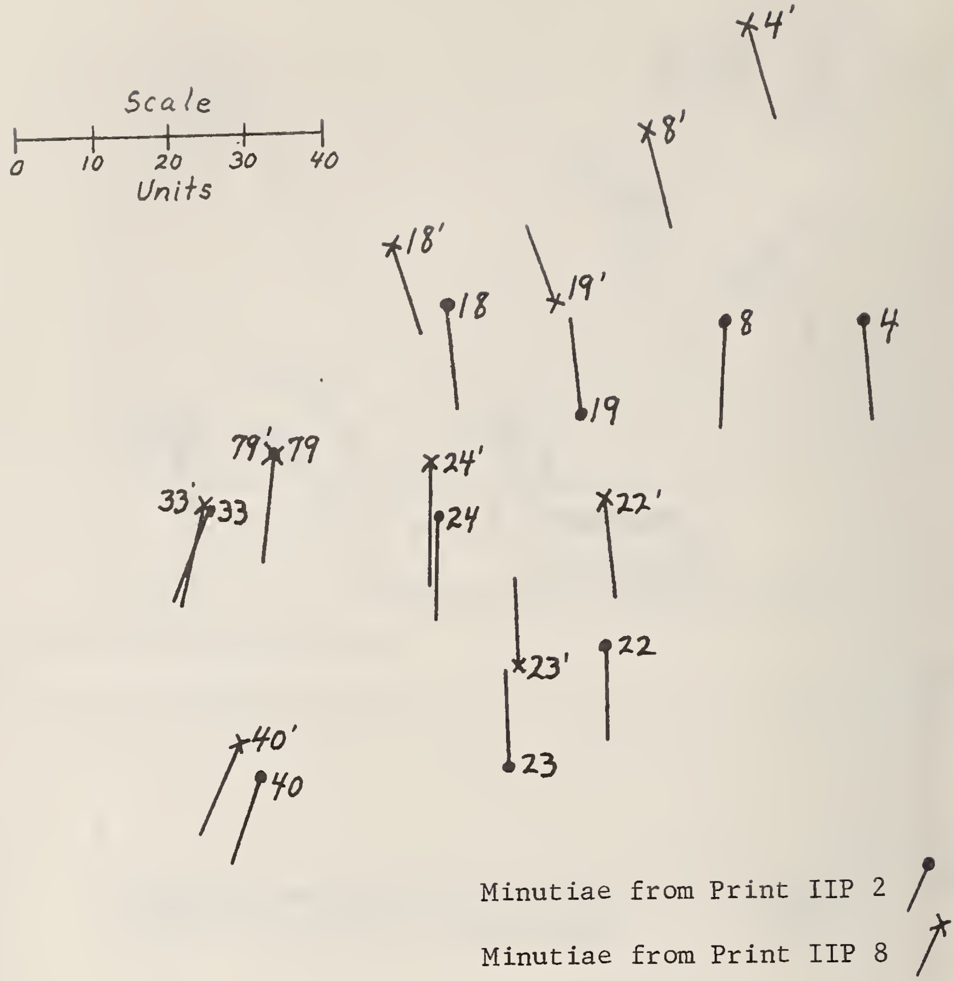
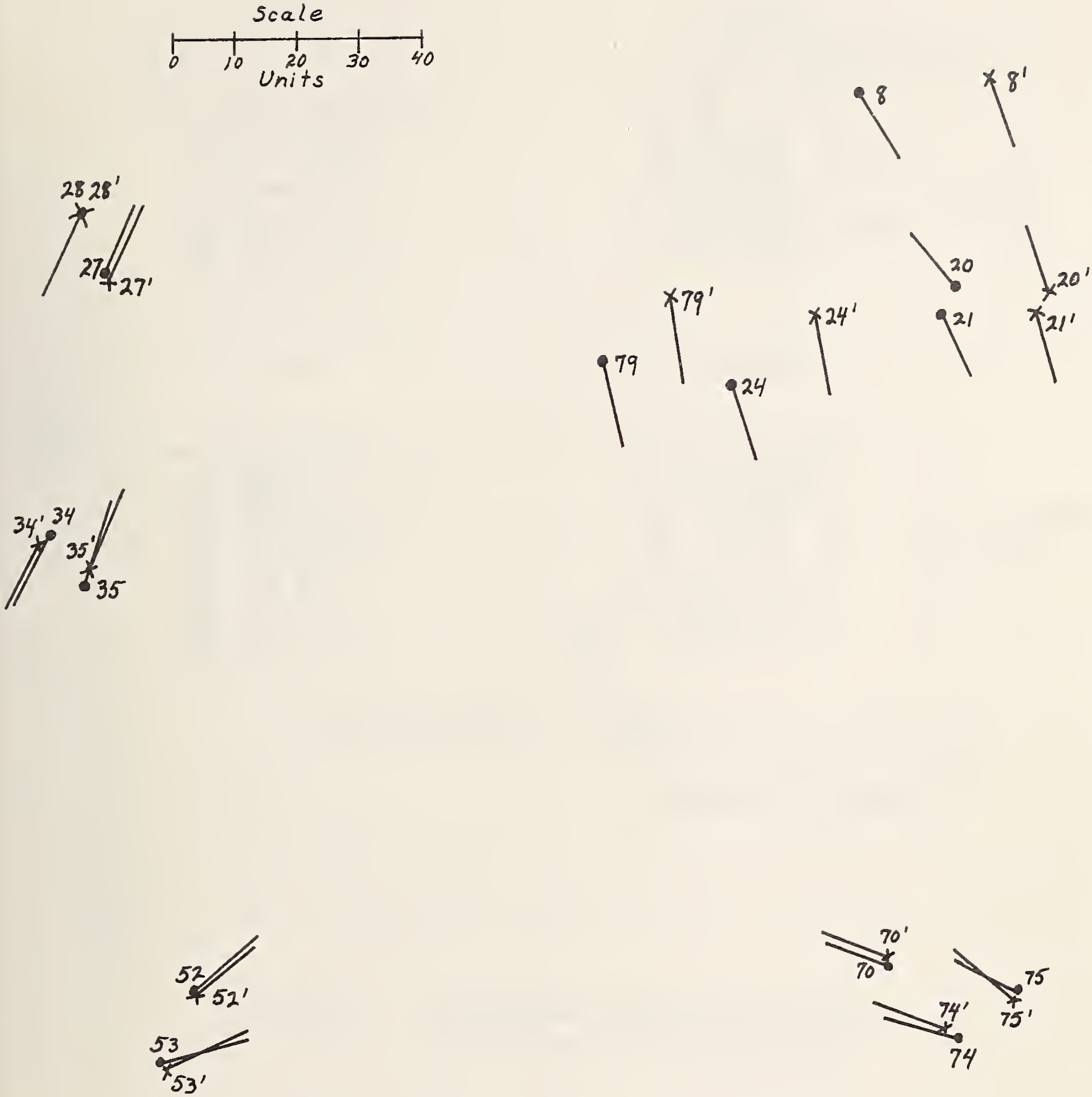


Figure 6. Superimposed Minutiae Tracings from Prints of the Same Finger



Minutiae from Print IIP 5

Minutiae from Print IIP 6

Figure 7. Superimposed Minutiae Tracings from Prints of the Same Finger

Print A

i	x	y	θ
1	48	252	67
2	27	190	226
3	68	174	205
4	136	233	111
5	142	181	327

Print B

j	x	y	θ
1	75	241	65
2	62	181	225
3	109	161	222
4	174	229	128
5	182	175	346
6	157	226	111

Print C

i	x	y	θ
1	38	217	56
2	27	154	223
3	89	244	15
4	143	210	115
5	117	175	300
6	153	128	334

Print D

j	x	y	θ
1	55	227	54
2	41	164	227
3	120	226	305
4	173	180	276
5	77	132	320
6	65	121	325
7	172	142	285

Figure 8. Minutiae Data

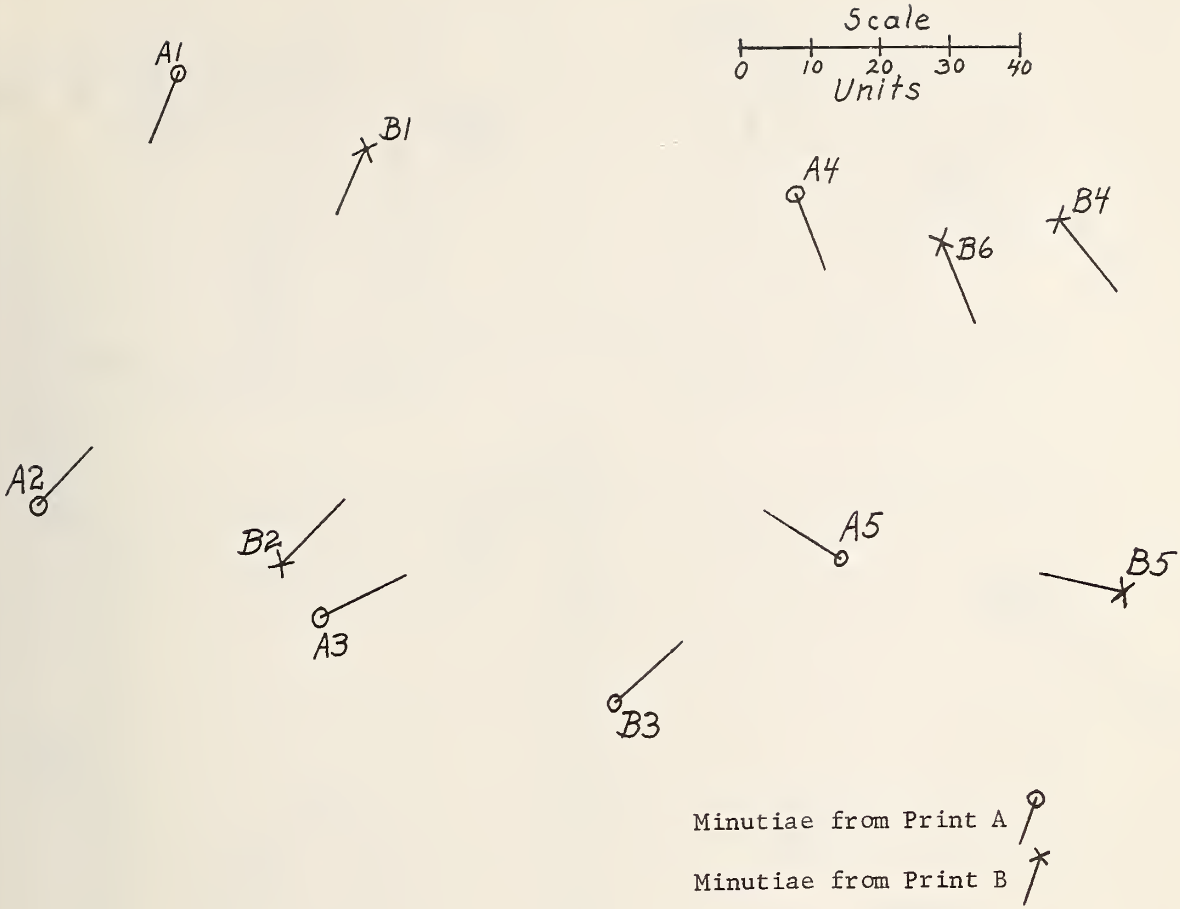


Figure 9. Superimposed Machine Read Minutiae from Prints of the Same Finger

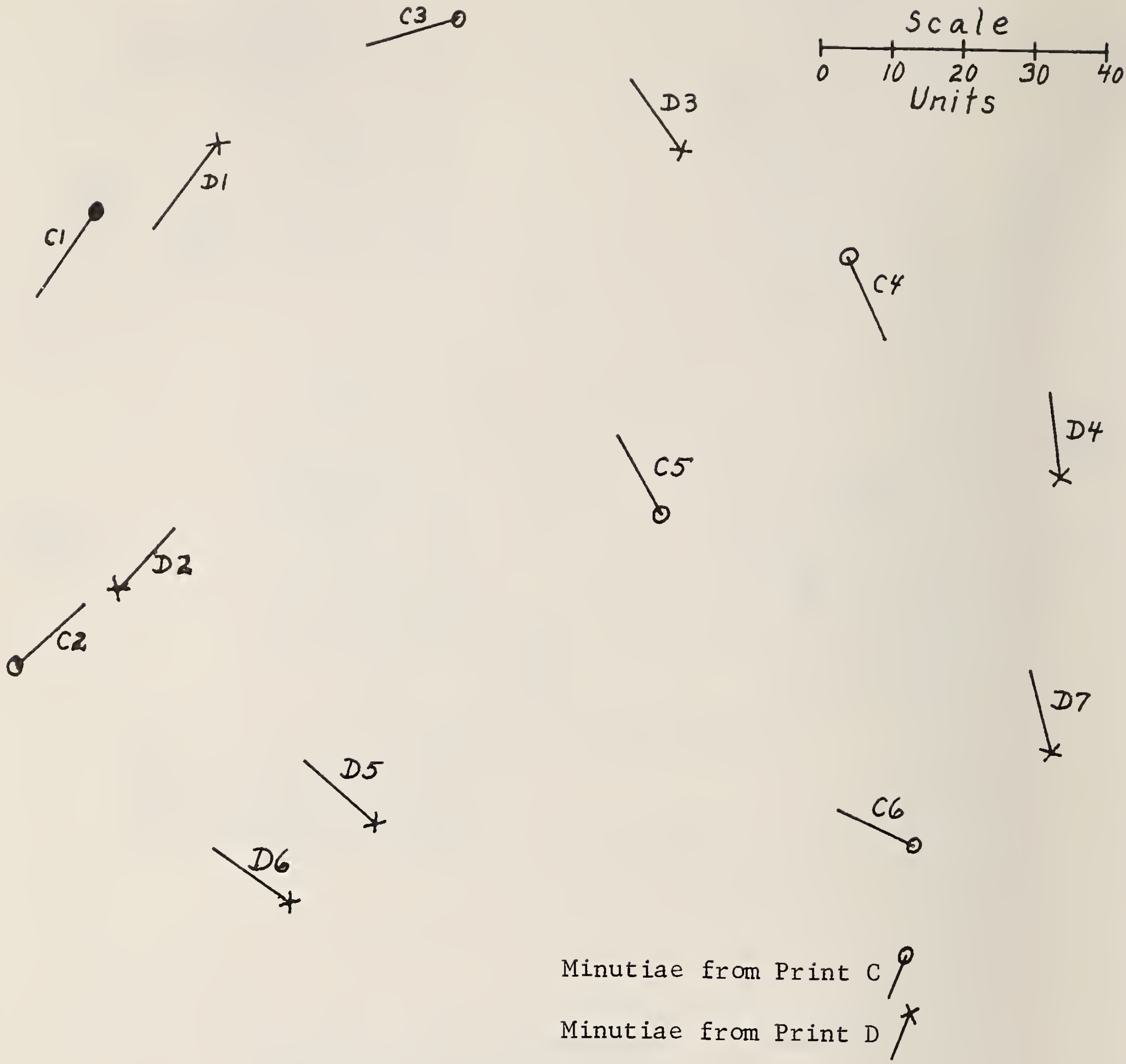


Figure 10. Superimposed Machine Read Minutiae from Prints of Different Fingers.

i	j	Δx	Δy	Δθ
1	1	-27	11	2
2	2	-35	9	1
3	2	6	-7	-20
3	3	-41	13	-17
4	4	-38	4	-17
4	6	-21	7	0
5	5	-40	6	-19

Figure 11. Difference Table for Prints A and B

i	j	Δx	Δy	Δθ
1	1	-17	-10	2
2	2	-14	-10	-4
5	3	-3	-51	-5
5	4	-56	-5	24
5	5	40	43	-20
5	6	52	54	-25
5	7	-55	33	15

Figure 12. Difference Table for Prints C and D

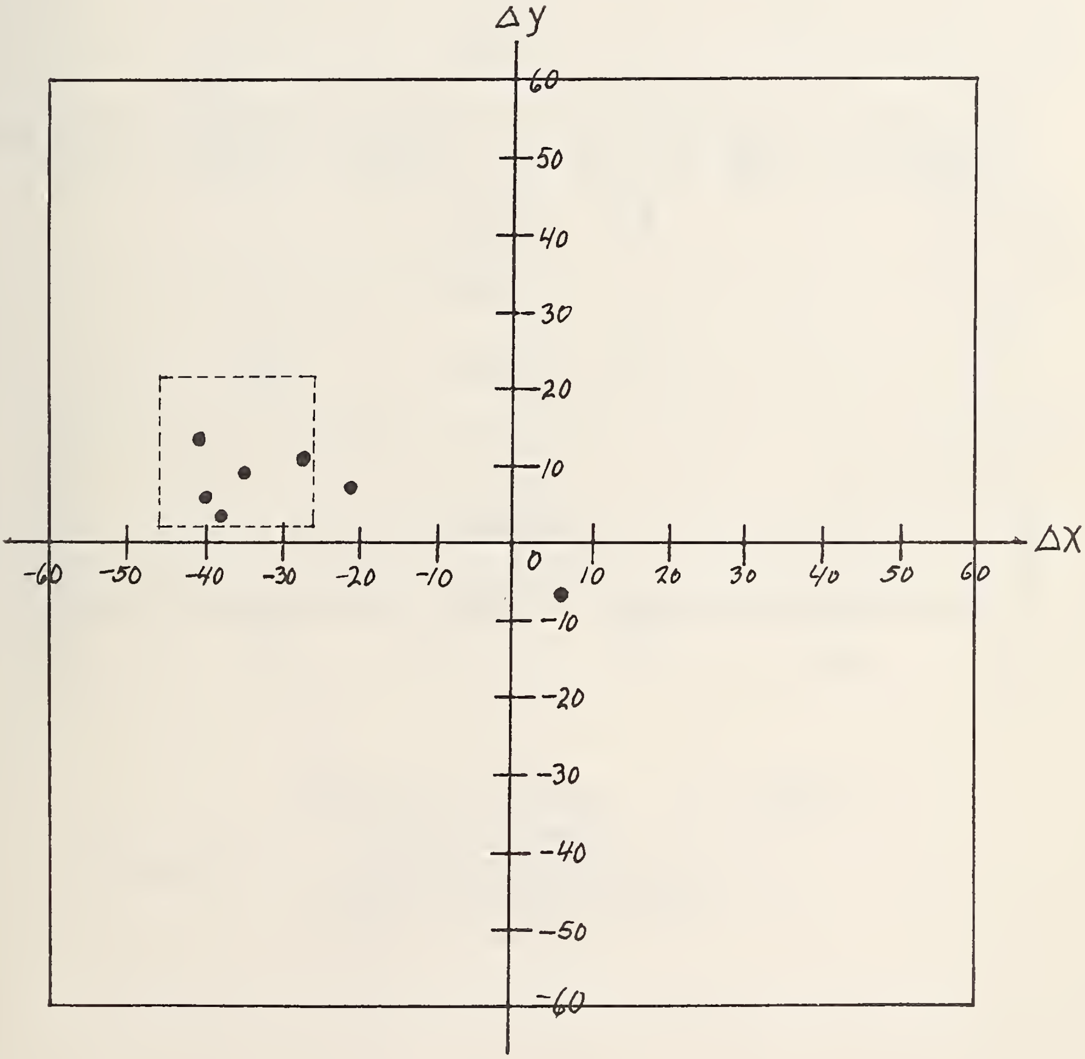


Figure 13. Difference Graph for Prints A and B of the Same Finger

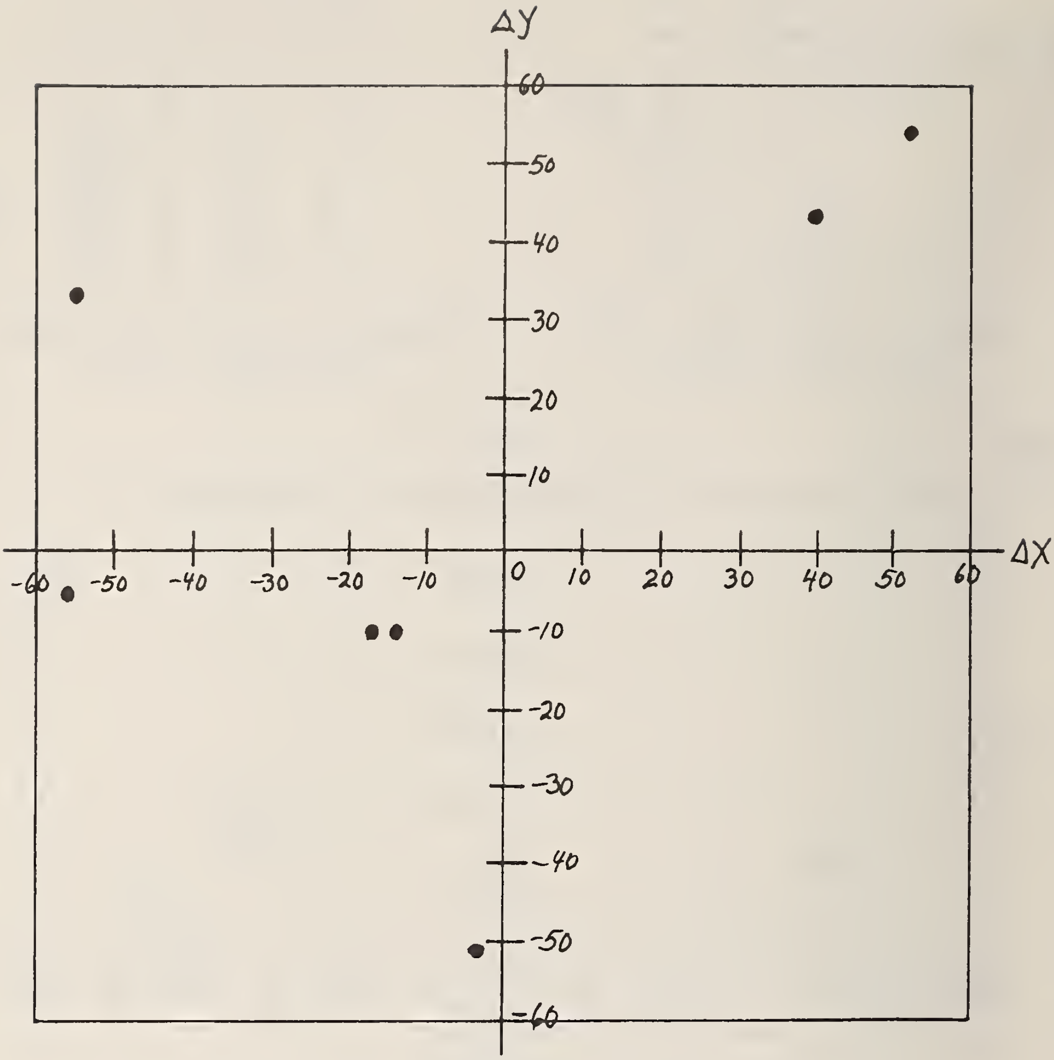


Figure 14. Difference Graph for Prints C and D of Different Fingers

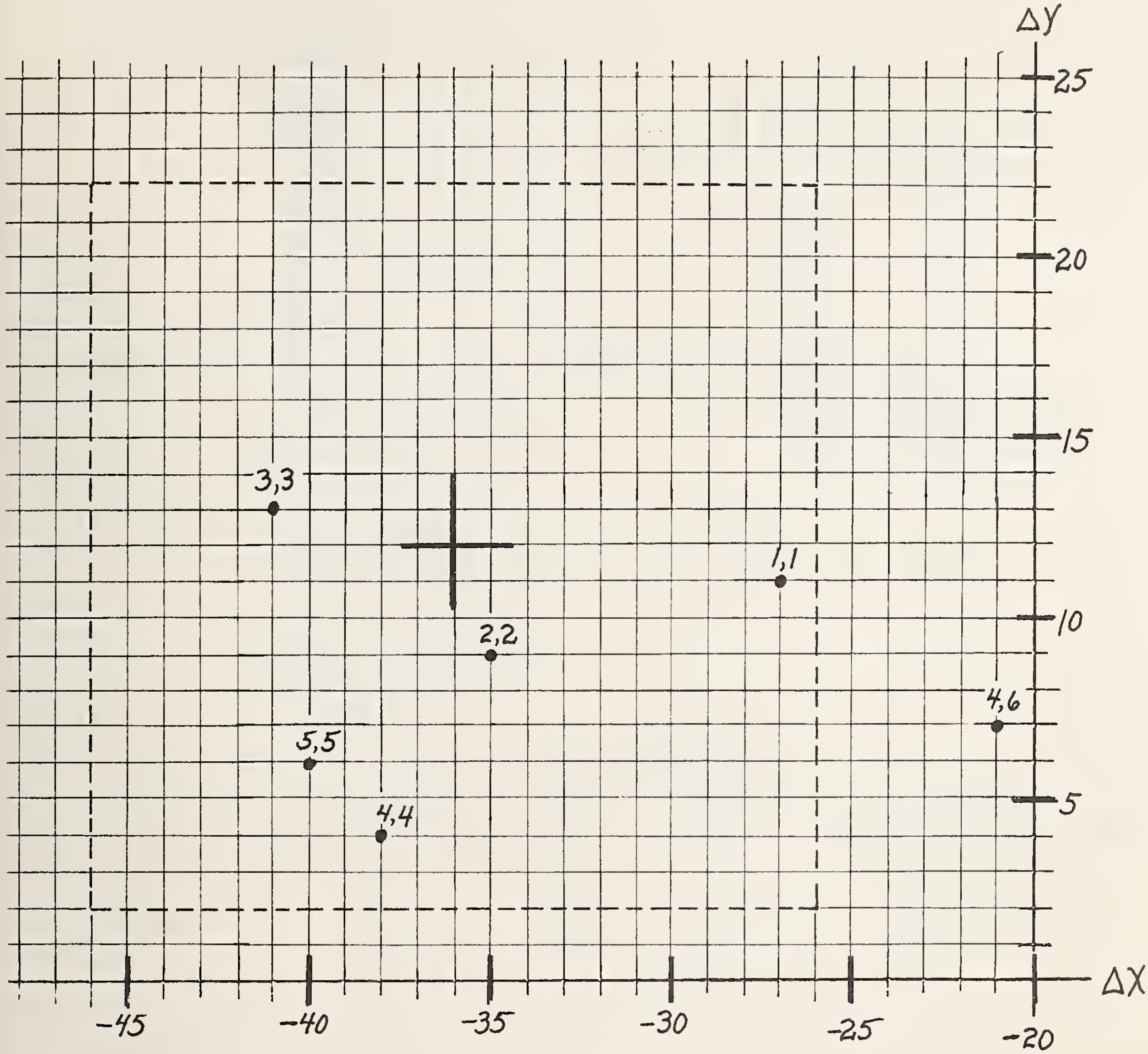


Figure 15. EnlargedPortion of Difference Graph for Prints A and B Shown in Figure 13.

From		Steps	Contribution to Score
point	to point	TR	KR-TR
1,1	---	>10	0
2,2	4,4	8	2
2,2	5,5	8	2
3,3	5,5	8	2
4,4	2,2	8	2
4,4	5,5	4	6
5,5	2,2	8	2
5,5	3,3	8	2
5,5	4,4	4	6
			R = 24

Figure 16. Computation of Score for Figure 15.

Interval	Distribution Δx	Distribution Δy	Center of Interval	
-60 to -55	0	0	-60	
-54 to -43	0	0	-48	
-42 to -31	4	0	-36	Peak Δx
-30 to -19	2	0	-24	
-18 to - 7	0	1	-12	
- 6 to 5	0	1	0	
6 to 17	1	5	12	Peak Δy
18 to 29	0	0	24	
30 to 41	0	0	36	
42 to 53	0	0	48	
54 to 60	0	0	60	

Figure 17. Distribution of Δx and Δy for Print A vs Print B

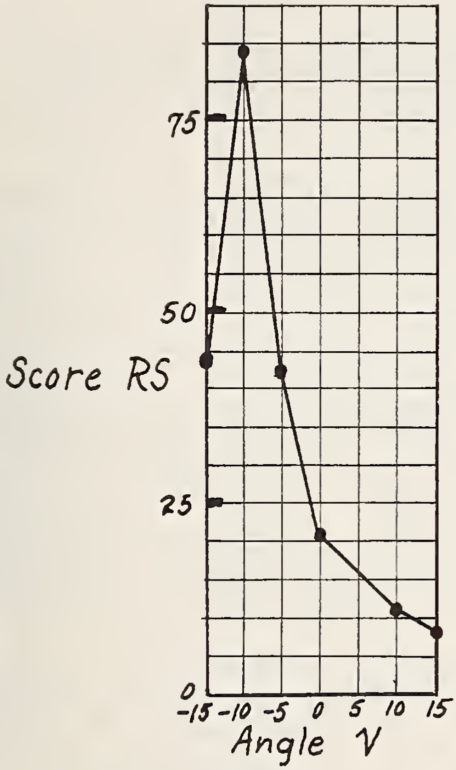


Figure 18. Results from M32 Comparison of Prints XVII 71 and XVIII 921 from the Same Finger

Set XXVII (Computer Run # 280)

Set XXVI

Print	1122	1132	1157	1167	1182	1187	1188	1212	1217	1242	1257	1332	1337	1492
272	119	30	13	24	20	28	31	14	15	20	23	8	22	20
282	34	78	12	21	19	7	12	10	15	40	18	14	10	12
307	10	12	104	20	26	31	30	16	20	9	22	15	16	19
317	29	20	21	75	36	17	34	16	18	32	31	32	21	25
332	13	19	30	15	266	10	24	30	16	6	8	13	17	23
337	12	29	39	8	31	86	22	15	11	17	28	15	20	30
338	24	26	15	22	24	25	105	6	16	27	39	17	42	17
362	20	19	25	15	22	5	14	158	5	12	3	8	22	15
367	14	17	24	24	10	26	21	13	115	13	32	1	16	18
392	28	32	10	19	19	11	10	19	6	109	18	20	7	20
407	40	23	14	34	30	17	45	28	22	22	132	9	15	28
482	7	10	3	10	18	14	19	12	11	10	8	145	19	15
487	27	8	15	29	17	10	31	0	21	19	19	16	143	19
642	20	18	10	28	30	29	19	21	15	22	22	14	27	116

Figure 19 Score Matrix for M27 Matching of Good-Quality Machine-Read Prints

OS = 60
CS = 51
AA = 15

FINGERPRINT IMPRESSIONS				MINUTIAE READER				MATCHER									
Pairs of Print Sets	Name of Search Set	Name of File Set	No. of Prints In Set	No. of Minutiae Per Print Read By Reader			Notes	Computer Run Number	Matcher	Parameters					Scores		
									M19	LS	LØ		SM	KR			
				min	ave	max			M27	LS1	LØ1	LS2	LØ2	KR	OS	CS	AA
A Average Quality Rolled Prints	XIII		20	42	75.7	111	Manually read with X-axis parallel to crease	199	M27	100	25	15	18	10	149	124	18
		XIV	20	36	69.6	105		218	M27	100	35	15	18	10	153	129	17
							See text										
B Same Prints as A	XIII C		20	13	24.0	39	Minutiae from 6mm circle at core of Pair A prints	236	M19	15	18		10	10	141	76	
		XIV C	20	14	22.9	34		237	M27	60	25	15	18	10	145	76	18
C Average Quality Rolled Prints	XVII		21	57	80.6	117	Machine read with finger-box on card centered in reader	201	M27	100	25	15	18	10	1175	750	28
		XVIII	21	53	82.2	124		224	M27	120	30	15	18	10	288	190	26
								285	M32	100	25	15	18	10	415	121	31
							See text	177	M19	15	18		20	10	108	59	
D Same Prints as C	XXIII		21	95	159.1	258	Machine read with manually centered & oriented prints	254	M27	35	15	10	15	8	250	126	33
		XXIV	21	39	150.6	250		255	M27	35	15	10	10	8	206	155	31
								256	M27	35	15	10	15	10	249	135	36
								257	M27	30	15	10	15	10	317	200	36
								258	M27	35	10	10	10	10	206	153	31
E Selected as "good looking" Rolled Prints	XXX		14	39	80.7	124	Machine read with finger-box on card centered in reader	282	M27	60	15	10	15	10	149	80	15
		XXXI	14	40	74.1	98		283	M27	60	25	15	18	10	153	102	19
							See text	286	M19	18	15		20	10	96	58	
								287	M19	15	15		5	10	88	50	
								289	M27	25	15	10	15	10	94	40	8
								290	M27	20	15	10	15	10	100	33	7
								291	M27	20	10	10	10	10	114	57	4

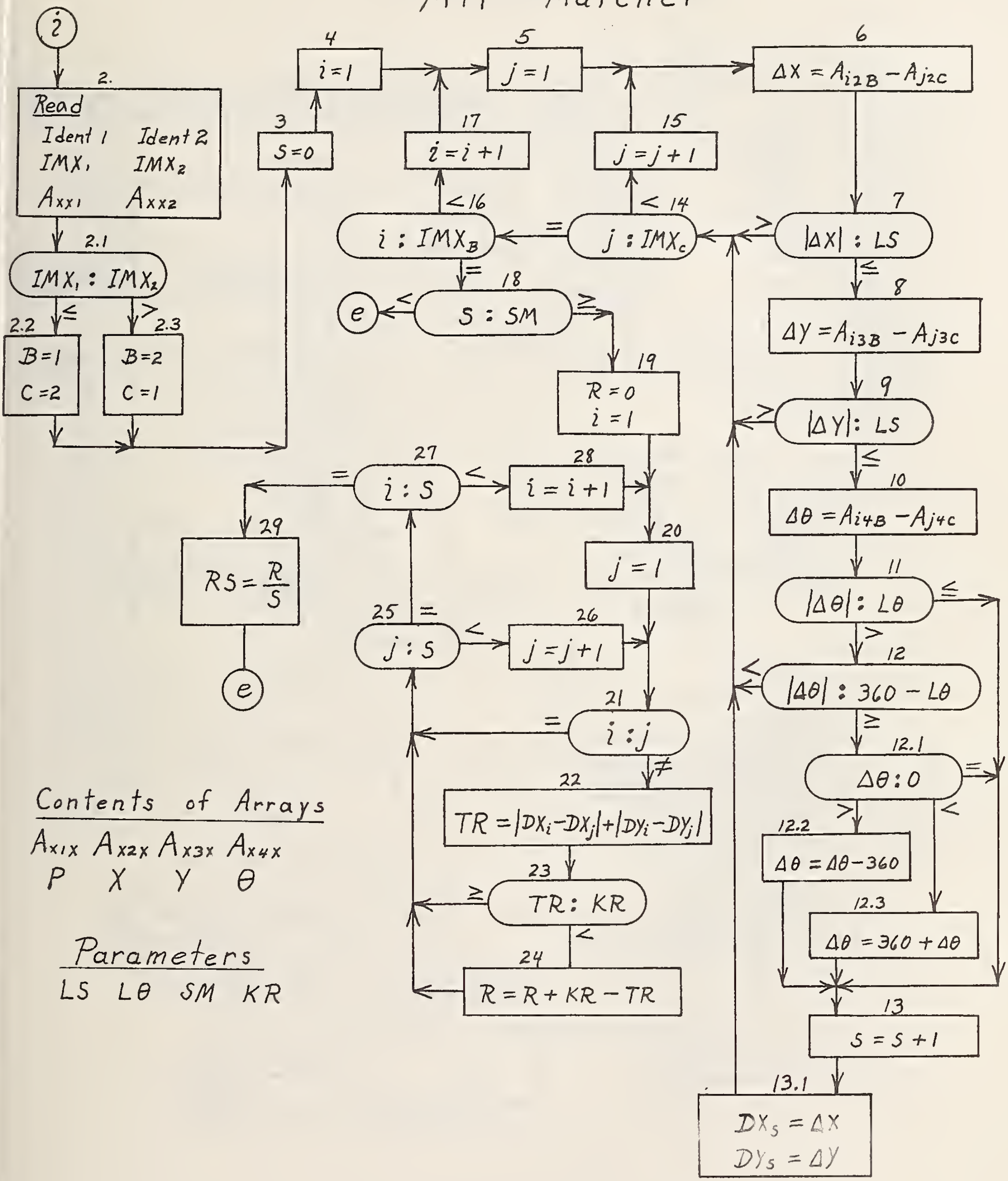
Figure 20 Part 1 Summarized Results Using Statistical Matcher

FINGERPRINT IMPRESSIONS				MINUTIAE READER				MATCHER									
Pairs of Print Sets	Name of Search Set	Name of File Set	No. of Prints In Set	No. of Minutiae Per Print Read By Reader			Notes	Computer Run Number	Matcher	Parameters					Scores		
									M19	LS	Lθ		SM	KR			
				min	ave	max			M27	LS1	Lθ1	LS2	Lθ2	KR	OS	CS	AA
F							Machine	259	M27	35	15	10	15	8	74	67	17
Same	XXVI		14	81	134.7	238	read with	260	M27	35	15	10	10	8	93	93	15
Prints							manually	261	M27	35	15	10	15	10	86	67	19
as E		XXVII	14	80	128.9	175	centered	262	M27	30	15	10	15	10	80	66	19
							& oriented	263	M27	35	10	10	10	10	57	46	17
							prints	278	M27	30	10	10	10	10	59	56	17
								279	M27	25	15	10	15	10	77	58	18
								280	M27	20	10	10	10	10	60	51	15
G							Machine										
Average Quality	XIX		17	23	38.5	54	read with										
Plain							prints	220	M27	120	30	15	18	10	560	200	21
Prints		XX	17	22	37.2	78	approx.										
							centered	181	M19	15	18		10	10	111	58	
							in reader										
							See text										
H								264	M27	35	15	10	15	8	100	90	20
Selected as "good	XXVIII		10	36	58.8	77		265	M27	35	15	10	10	8	107	100	18
								266	M27	35	15	10	15	10	97	97	23
looking"		XXIX	10	51	68.3	116	Machine	267	M27	30	15	10	15	10	73	66	23
Plain							read with	268	M27	35	10	10	10	10	86	81	19
Prints							manually	269	M27	30	15	10	15	8	65	58	20
							centered	270	M27	30	10	10	10	10	71	71	19
							& oriented	271	M27	30	15	10	10	10	94	78	20
							prints	272	M27	30	15	10	10	8	94	76	17
								273	M27	25	10	10	10	10	69	69	19
								274	M27	25	15	10	15	10	65	58	21
								275	M27	20	15	10	15	10	81	60	20
								276	M27	20	10	10	10	10	70	65	19

Figure 20 Part 2

Flow Chart 1

M19 Matcher



Contents of Arrays

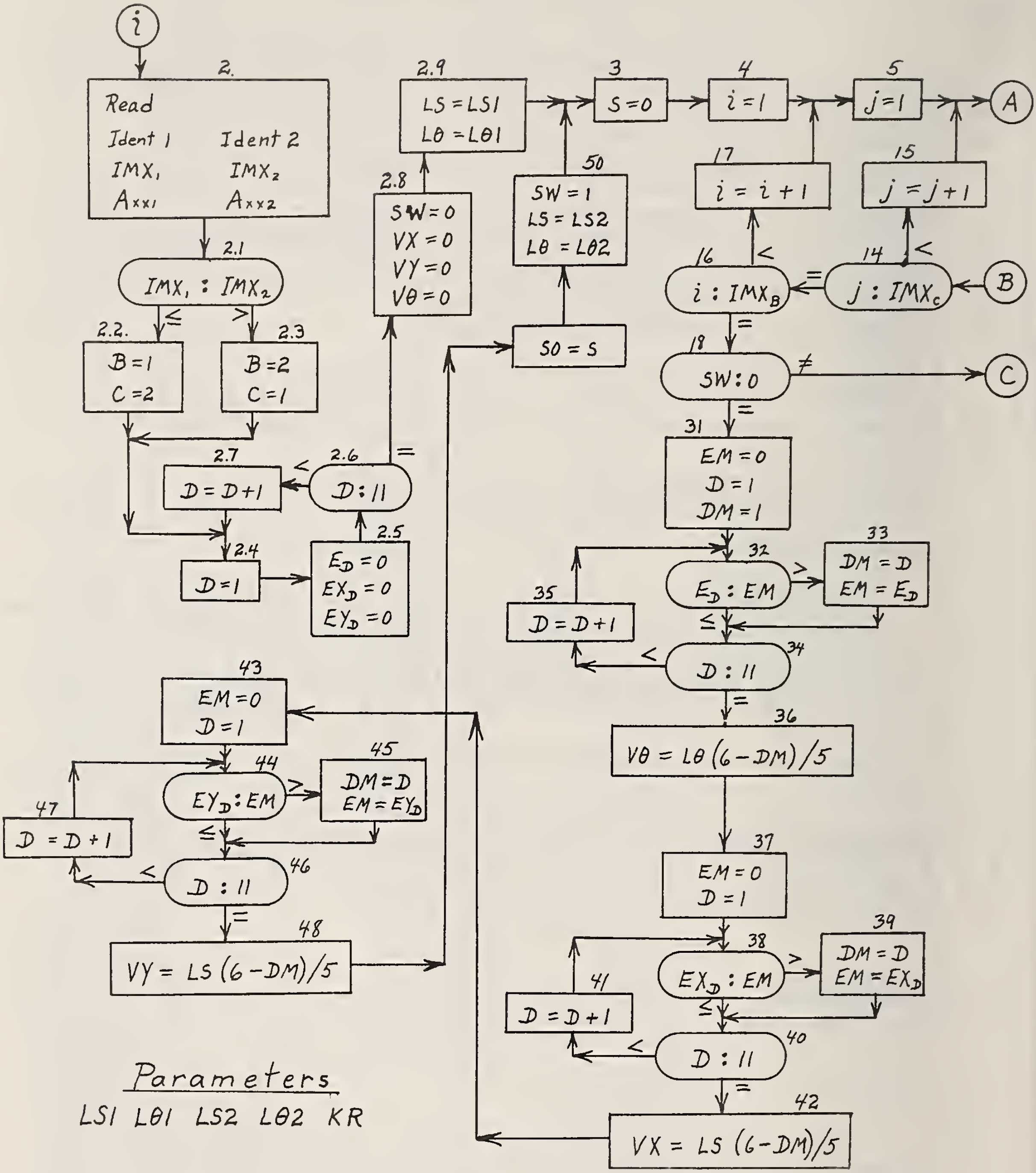
A_{x1x} A_{x2x} A_{x3x} A_{x4x}

P X Y θ

Parameters

LS $L\theta$ SM KR

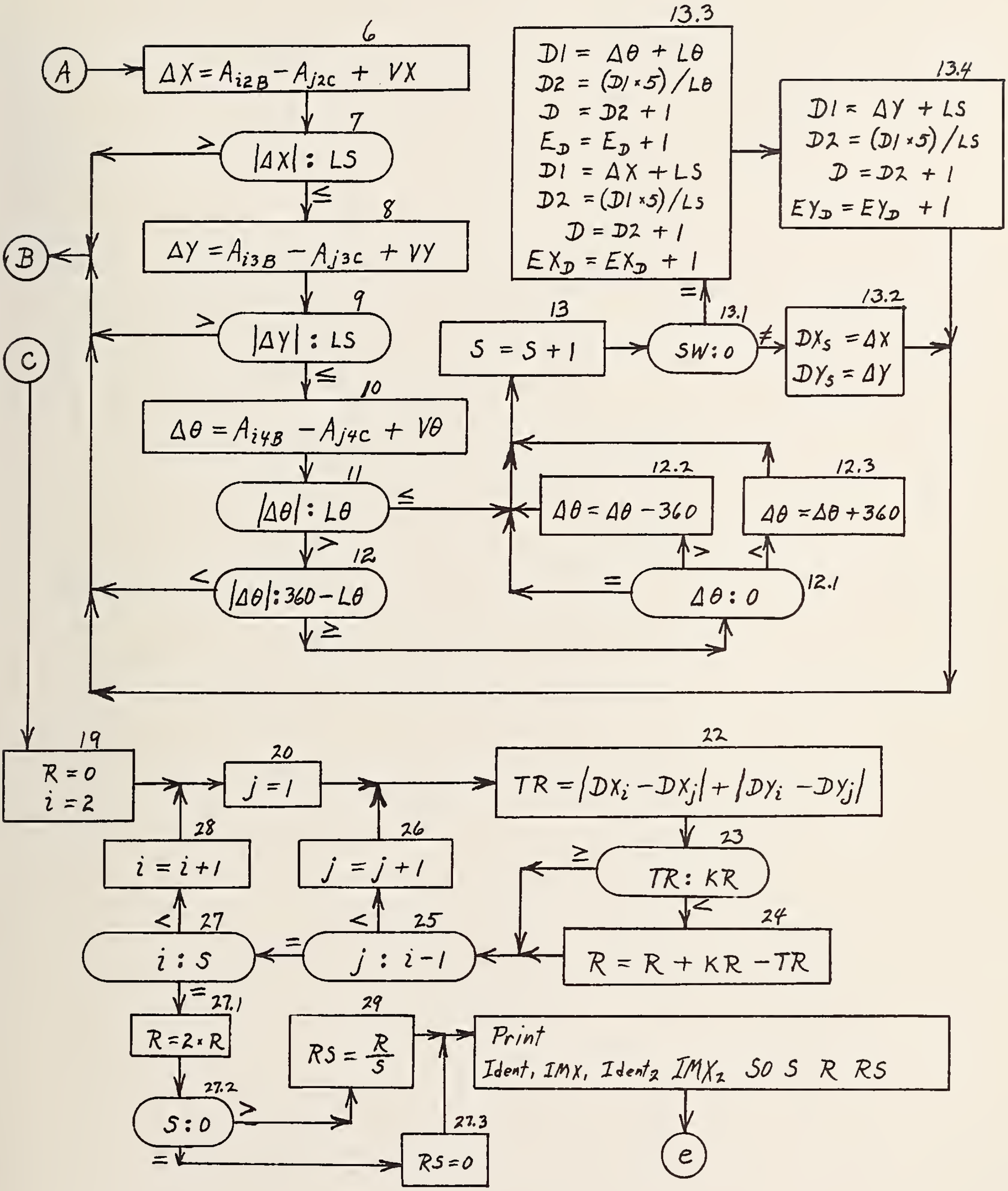
Flow Chart 2 Part 1
M27 Matcher



Parameters

LS1 Lθ1 LS2 Lθ2 KR

Flow Chart 2 Part 2
M27 Matcher Cont.



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